United States Army Signal Center, Fort Gordon, Georgia
Leader College of Information Technology

Improving Spectral Efficiency

Functional Area 24 Telecommunications Systems Engineering Course Class 02-01

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28 May 2002

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1. Thesis Statement

In light of increasing capacity demand on the military radio frequency (RF) spectrum, what are the spectral efficiencies that the US Army can achieve if emerging RF technologies and management techniques are implemented to satisfy the implied spectral requirements as set forth in Joint Vision 2010 and Joint Vision 2020.

2. Scope

Given that the US Army and the Department of Defense have inextricably committed to using the spectrum, our goal was to identify some of the state of art research technologies that are emerging that will enable the Army to maximize the available spectrum in an environment of ever increasing demands. We have limited our focus on technologies that are good candidates for further inclusion in military systems at the Brigade level and below. Our discussion in no way is to be considered exhaustive and is only intended to provide the reader with an understanding of their potential benefits. The emerging technologies that are discussed are being developed by both military and civilian agency and activities.

We will also attempt to describe some of the competing commercial influences and the current US system for resolving this competitive and contentious situation.

3. Background

3.1 RF Spectrum

The modern day use of the RF spectrum traces it origins back to the efforts of many talented scientists, inventors and entrepreneurs. Historically, three men are widely regarded as having made the greatest contributions. The first was an English physicist, James Clerk Maxwell (1831-1879), who in 1865 theorized and proved mathematically the existence of electromagnetic waves. The second was a German physicist, Heinrich Rudolf Hertz (1857-1894), who in 1888 demonstrated the existence of electromagnetic waves by transmitting and receiving a signal across a room. In honor of his work, the unit of frequency measure, Hz, bears his name. Figure 1 is a typical depiction of a portion of the electromagnetic spectrum. The third was an Italian electrical engineer, Guglielmo Marconi (1874-1937), who in 1897 received the first patent in the history of radio. His first radio was capable of transmitting signals only over 2 kilometers. By December 12, 1901, his radio was capable of transmitting signals across the Atlantic Ocean.[1]

Today, the usable RF spectrum is considered to be a valuable, but limited, national resource. It ranges from 3 Hz to 300 GHz. This band is further divided into subcatagories (ex. HF, VHF, SHF) that exhibit distinct propagation characteristics and susceptibility to atmospheric absorption and interference. Generally increases in frequency result in an increase in vulnerability to atmospheric conditions.

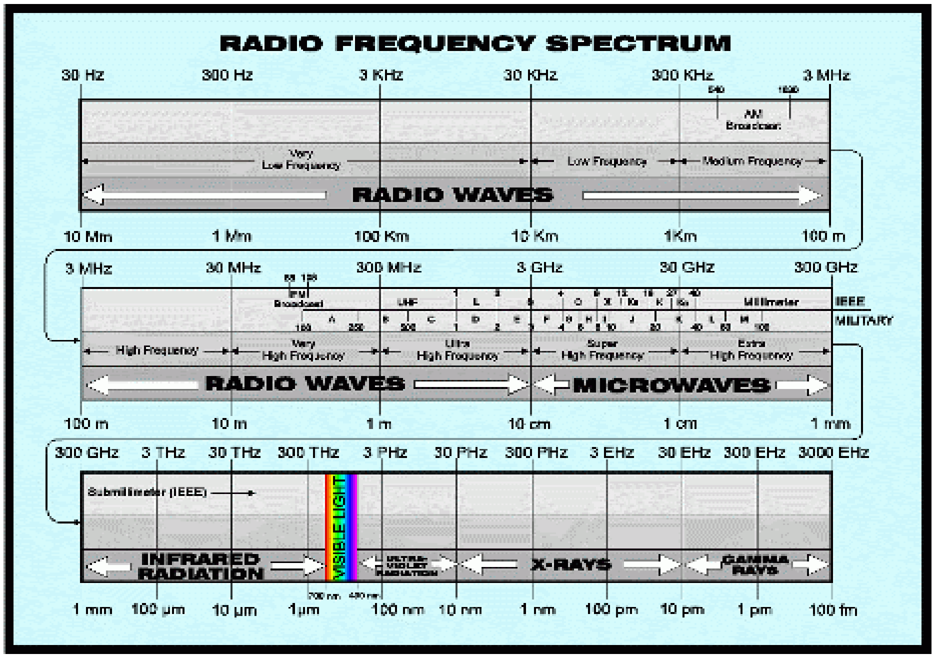

Figure 1. RF Spectrum

3.2 RF spectrum and the US Army

The Army owes its use of wireless systems to the leadership of MG Aldophus W. Greely (1844-1935). MG Greely, as the Chief of the Signal Corps, directed close attention be paid the work being done by Marconi. The Signal Corps has been employing systems that depend upon unhindered access to RF spectrum since 1899. This first AM wireless telegraph system installed in New York Harbor would mark the beginning of the US Army's RF utilization efforts.[3] Research and development efforts in the 20th century have produced a wide array systems and applications for would witness the proliferation of RF systems in both the public and private sector.

The public sector witnessed advances in military fixed and mobile voice and data communications, weapons control and guidance, radar, telemetry and radio navigation systems. Many of the current commercial communications system owe their technological birth to military funded research. The current trend for future military development is toward digital network centric emitters. This implies that emitters actively establish connections with neighboring emitters and relay information. This reduces the transmit power requirements of every radio in the network.

The private sector included advances in broadcast communications (TV and Radio), voice and data communications (Cellular, Trunk and Packet Radio Services). Recent military history is replete with examples of commercial technology being used by the military. This includes the commercial trunk radios that are used by Military Police in their Garrison security role and also the proliferation of cellular telephones and pagers in Army organization around the world. This forces any one looking at commercial technology to realize that consumer versions of commercial technologies will always have a place in military communications during peacetime.

3.3 Unique Military Design Considerations

Several key aspects of modulation must be considered when selecting a modulation scheme for military use; the most important of these is security. Figure 2 below shows the various ways in which a signal could be exploited. All modern modulation schemes can transport digital traffic, so current encryption devices will still be effective in avoiding exploitation; however, the additional concerns that are inherent to modulation are detection probability and anti-jam capability. Detection avoidance will inherently prevent disruption and exploitation of communications and could be considered the most important.

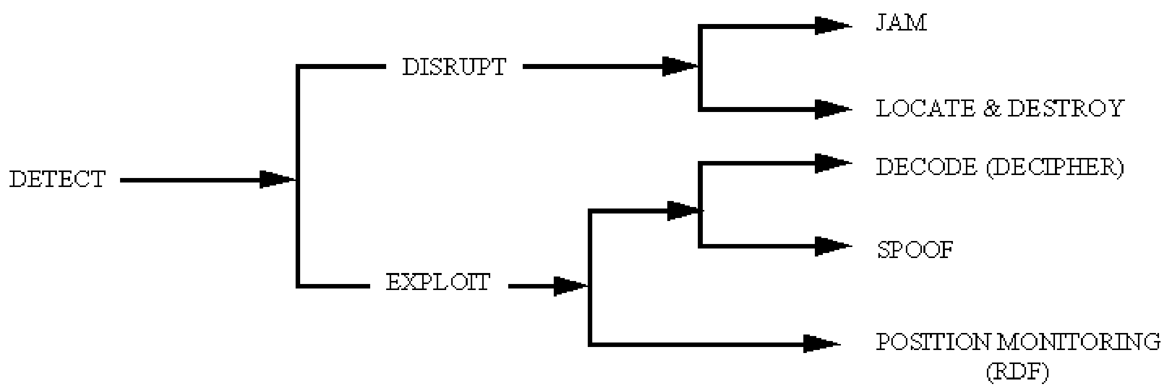

Figure 2: Electronic Warfare Overview for Military Systems [4]

Detection probability is best circumvented by minimizing power spectral density signature of the transmitter. The transmitter and receiver must be intelligent enough to negotiate the lowest possible power setting in order to effectively communicate. It will be shown later than some modulation techniques are designed to transmit using low power, thus reducing the probability of detection.

Anti-Jamming is a denial of service attack that can also be avoided through intelligent transmitters and receivers that dynamically adjust to their environment and change frequencies when jamming occurs. Current wireless systems such as SINCGARS use frequency hopping to avoid jamming. A modulation scheme that has the inherent ability to use multiple frequency bands is best suited for anti-jamming.

Other considerations that have an impact on wireless systems are Spectral efficiency, Scalability, Resiliency, and the Environment. Spectral Efficiency is the primary subject of this paper and will be discussed in detail in later sections. Scalability is a function of a modulation schemes ability to operate over a wide range of frequencies; only those wideband techniques will be considered in this paper. Resiliency is the same concept as anti-jamming, where the scheme has the inherent ability to continue to be effective under adverse conditions that affect the signal to noise ratio (SNR) at the receiver. The environment (terrain, man-made and natural obstacles, and the earth's curvature) effect the transmission distance of a wireless signal. These obstacles are primarily a function of the particular frequency in use, but can also cause multi-path fading or be used as an advantage to increase spectral efficiency as will be shown later.

3.4 Modulation, Channel Capacity and Spectral Efficiency

In order to properly compare modulation techniques, a brief discussion of modulation, Shannon's Capacity Theorem and spectral efficiency is in order. First, several key definitions must be understood before continuing. Bandwidth in this paper is defined as the range of frequencies in Hertz used by a particular modulation scheme. Channel capacity is defined as the maximum data rate that can be transmitted over a given bandwidth in bits per second (bps) and Spectral Efficiency is defined as the channel capacity divided by the bandwidth in bits per second per Hertz (bps/Hz).

This paper addresses only modulation techniques, although there are other methods of data compression that can increase efficiency at higher protocol layers. In terms of the Open Systems Interconnect (OSI) model, modulation would be considered the physical layer which can be divided into the sub-layers as shown in figure 3. for the purpose of this paper. All modern efficient and reliable modulation schemes use a combination of phase and frequency modulation. The most common schemes are Bi-Polar Shift Keying (BPSK), Quadrature Phase Shift Keying (QPSK), and Quadrature-Amplitude Modulation (QAM). The two common methods of allowing a receiver and transmitter to communicate simultaneously is accomplished through Time Division Duplexing (TDD) or Frequency Division Duplexing (FDD). Additionally, the methods for allowing multiple users to access the same bandwidth is accomplished through Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA), or Code Division Multiple Access (CDMA).

Figure 3: Physical Layer Modulation Model

The theoretical maximum channel capacity of a given bandwidth of a continuous channel with a peak power limitation was defined by Claude Shannon as shown in Equation (1):

$$C = W \log_2 (1 + {}^{S}/_{N}) \text{ [5]} \tag{1}$$

Where C is the capacity in bits per second, W is the bandwidth in Hertz, and S/N is the peak signal power over average white noise power [5]. Extending Shannon's equation to define spectral efficiency as the capacity over the bandwidth, the maximum theoretical spectral efficiency can be defined as shown in equation (2):

$$\eta = {}^{C}/_{W} = \log_2 (1 + {}^{S}/_{N}) \tag{2}$$

Where η is the spectral efficiency in bits per second per Hertz. Therefore the maximum theoretical spectral efficiency of any bandwidth is strictly a function of the peak signal power over average white noise power. This will be the standard by which we will judge the efficiency of the modulation techniques described in the paper.

4. US Spectrum Allocation

4.1 National Management

There are two Federal Government agencies responsible for the day-to-day frequency use and management at the national level: The National Telecommunications and Information Administration (NTIA) and the Federal Communications Commission (FCC).

4.1.1 National Telecommunications and Information Administration (NTIA)

The NTIA controls the frequency assignments to Federal Government agencies; as well as establishes plans, policies, regulations and procedures—this is done in coordination with the FCC. The government agencies include the following:

- Department of Defense
- Law Enforcement & Security
- Transportation
- Resource Management
- NASA
- Federal Aviation Administration

The head of the NTIA is the Assistant Secretary of Commerce for Telecommunications and Information. He is also the principal advisor to the President for telecommunications issues.

Below the NTIA is the Interdepartment Radio Advisory Committee (IRAC). The NTIA chairs the IRAC and its subcommittees. There are twenty government departments and agencies that are members of the IRAC including the Army, Navy, Air Force, Coast Guard, Federal Emergency Management Agency, and the Federal Aviation Administration. The IRAC has an advisory relationship to the NTIA. [6]

New systems developed for military use must be approved by both the IRAC and the NTIA as being electromagnetically supportable at each stage of the Life Cycle System Management Model.(Planning, Experimental, Developmental, Operational) The DD Form 1494, Application for Equipment Frequency Allocation, is the tool used to document system operational approval. Even commercial systems that are pressed into military use are required to be documented with a DD Form 1494. [7]

4.1.2 Federal Communications Commission (FCC)

The FCC is responsible for frequency spectrum management to non-governmental agencies—the private industry and commercial entities. The applications fall into the following categories:

- Business Sector
- State and Local Authorities
- Entertainment Industry
- Commercial Industry
- Private Use

The FCC provides a liaison to the IRAC.

4.2 INTERNATIONAL MANAGEMENT

At the international level, the one hundred ninety-three member body, International Telecommunications Union (ITU), establishes the regulations, standardization, coordination, and development of international polices. It also manages the use of the radio-frequency spectrum and geo-stationary satellite orbit. The US Government and commercial satellites are registered through the ITU.

The NTIA and the FCC, in coordination with the Secretary of State and other agencies, plan, develop policies and programs as it relates to international telecommunications policies which best serve our national interests. Spectrum management also differs externally to the U.S. Other countries maintain a spectrum management agency, much like our NTIA. The management agency sub-divides the spectrum to maximize their country's interest. U.S. military request spectrum use through the State Department has the lead when conducting Status of Forces Agreement (SOFA) coordination with host nations.

4.3 SPECTRUM USE

The radio spectrum extends from Very Low Frequency (VLF, 3 Hz) to Extremely High Frequency (EHF, 300 GHz) Over all, about thirty percent is Federally controlled. Another thirty percent is non-Federally controlled frequencies, such as commercial entities. The final thirty percent are shared frequencies between the two. Figure 4 breaks down the different frequency bands and its typical users.

Tab. 1 Frequency ranges and typical users			
Frequency Band	**Designation**	**Propagation Characteristics**	**Typical Users**
3-30 kHz	Very Low Frequency (VLF)	Ground wave, low attenuation, day or night, high noise level	Long range navigation, submarine communication
30-300 kHz	Low Frequency (LF)	Similar to VLF but not quite as reliable	Long range navigation, marine radio beacons
300-3000 kHz	Medium Frequency (MF)	Ground wave and night skywave, low attenuation at night and high in day, atmospheric noise	AM broadcasting, maritime radio, direction finding, emerging frequencies
3-30 MHz	High Frequency (HF)	Ionospheric reflection varying with time of day, season and frequency	Amateur radio, military communication, international broadcasting, long distance aircraft and ship communication
30-300 MHz	Very High Frequency (VHF)	Nearly Line-Of-Sight (LOS) propagation, scattering caused by temperature inversions, cosmic noise	VHF television, FM broadcasting, FM two-way radio, AM aircraft communication, aircraft navigational aids
0.3-3 GHz	Ultra High Frequency (UHF)	LOS propagation, cosmic noise	UHF television, radar, microwave links, navigational aids
3-30 GHz	Super High Frequency (SHF)[a]	LOS propagation, rainfall attenuation above 10 GHz, atmospheric attenuation caused by oxygen and water vapour	Satellite communication, microwave links and radar
30-300 GHz	Extremely High Frequency (EHF)[b]	Same as above	Radar, experimental satellite uses
10^3 -10^7 GHz	Infrared, visible light, ultraviolet	LOS propagation, atmospheric attenuation caused by water vapour (fog) for some wavelengths (e.g, visible)	Optical communication

(a) Smaller bands within this range are also designated by the letters S,C,X or Ka and Ku
(b) The upper end of this band is called the mm (millimeter) band because of the wavelengths used

Figure 4: Frequency Ranges and Typical Users [8]

Federal organizations and agencies requesting to use of the spectrum submit its request to the NTIA. Likewise, non-Federal agencies, such as the commercial industry, submits their request to the FCC.

4.4 COMPETING FOR BANDWIDTH

The spectrum is sub-divided and allocated to between Federal agency use and non-Federal use, i.e. those govern by the FCC. Those allocations are further sub-divided down to the lowest management office. As a limited resource, by default, the spectrum is heavily competed for and "shared." Increasing requirements demands a larger burden on a limited spectrum. Consequently, competition for use occurs at every level and between services, agencies, and organizations.

On the local management level, the user can be characterized as a primary user or a secondary user. Geographic and utilization requirements may determine a primary user but in other cases resort to a secondary user. For example, on a military installation, a unit can be the primary user for a particular frequency band only within the confines of the training area. Meanwhile, that same frequency band could be assigned to another organization at distant location. Aside from assignment of operational frequencies, the management office must de-conflict the emitters within a given geographical area to separate the users. With increase use of radio frequency emitters in a given area in the last decade, interference between users had been more prevalent.

Technology advancement also competes for use of the spectrum. New military radio systems or commercial radio systems must undergo an approval process from the NTIA. One of the concerns with new systems is the interference with other systems within a dense population of emitters. For example, when Ultrawideband (UWB) systems were approved, there were safety concerns with interference with Global Positioning System (GPS) receivers. GPS operates in on two frequencies: 1575.42 MHz and 1227.60 MHz. A compatibility analysis conducted by the NTIA concluded that UWB systems did interfere with GPS system by elevating the noise floor. In the study, interference were noted when 1Mhz, 5 MHz, and 20MHz frequencies (three of four modulation frequencies) were used in modulating signals in UWB systems. Surprisingly, one would tend to believe interference would be at the two GPS operating frequencies noted above, rather than at the noise floor level.[9]

5. Army Spectrum Management

5.1 Key Players [10]

The Army's spectrum management efforts are directed by the Director of Information Systems for Command, Control, Communications and Computers (DISC4). His principle advisor, the Army Spectrum Manager (ASM), is responsible for the development of Army spectrum management policy and guidance.
The Army Spectrum Management policy has three goal:

- To develop and efficiently manage Army use of the spectrum during allocation, allotment, and assignment processes and thereby minimize the potential for interference during the fielding and employment of spectrum dependent equipment.

- To obtain and manage the frequency resources to support Information Mission (IM) responsibilities, activities, and programs relating to the disciplines of telecommunications, automation, visual information, records management, and publications and printing.

- To provide spectrum signal characterization, measurement, and enforcement procedures for continued operation in the Army, joint and combined environment.

In addition to his policy development responsibilities, the ASM performs three very important functions that are critical for the Army to meet these goals:

- Serves as the principle Army negotiator/spokesman for Army domestic discussions, as a member of the IRAC, a member of the Radio Communications Bureau, a member of the Combined Communications Electronics Board Frequency Panel, a member of the United States Military Communications-Electronics Board (USMCEB) Joint Frequency Panel and represents the spectrum management requirements in the Army Systems Acquisition Review Council.

- Serves as the principle Army negotiator/spokesman for Army international discussions, either through the US Department of State on a Government-to-Government level; through the "Status of Forces" in cases of host government relationships; or for International Telecommunications Union meetings.

- Administers the Army Interference Resolution Program, which involves reporting and coordinating the resolution of serious electromagnetic interference incidents with both Army and other services activities, to include the JSC Joint Spectrum Resolution team, US civilian telecommunications organizations and host nations, if required.

Commanders at all level within the Army from MACOM down to Post, Camp and Station level are charged with the responsibility to adequately manage and supervise the use of spectrum with there area of operations. This function is usually delegated to the Deputy Chief of Staff for Information Management (DCSIM/G-6/Signal Officer), who is assisted by a frequency manager. The local frequency managers serve on the front line in the Army system and rely upon automated software, to statically assign frequencies to systems on a non-interference basis.

5.2 The Spectrum Management Tools

The complexity of spectrum management dictate that major efficiencies can be realized if computer power is utilized to avoid electromagnetic interference. The current Army system of choice is the Joint Spectrum Management System - Spectrum XXI, it was designed under the direction of the Joint Spectrum Center (JSC). Spectrum XXI is a modeling and frequency analysis program that utilizes multiple equipment, terrain, and frequency assignment databases to predict the occurrence of electromagnetic interference. The Army also uses other software programs to manage its RF environment that include the Revised Battlefield Electronic CEOI System (RBECS), the Network Planning Terminal (NPT) and ISYSCON.

The one limitation that all these programs have is that they are attempting to manage a very dynamic entity like the spectrum in a static manner. This results in inefficient frequency assignments because the program engines have to error on the side of caution and avoid the potential of interference. Once a frequency assignment is selected by one of these programs, it is no guarantee that the selected frequency will be electromagnetically compatible with other devices in the area. The causes of this interference can range from equipment malfunction, to improper system installation and antenna placement, or incomplete information in the databases used by the software. The net effect is that these tools are not fool proof.

6. Current RF technology

The current trend in Military RF systems is toward the networked radio, a radio that functions as an active member in a community of its peers. Examples of these systems include the Enhanced Position Location Reporting System (EPLRS), the Near-Term Digital Radio and the Single Channel Ground Airborne Radio System with the Advance System Improvement Program (ASIP). Collectively these systems form a wireless infrastructure that enables a brigade to disseminate large amounts of information. Another thing that all these platforms have in common is embedded GPS receivers.

The EPLRS and the NTDR both use TDMA as their multiple access protocol and TDD is used to enable two-way communications. The SINCGARS uses CSMA to pass packetized traffic from radio to radio and is capable of using FDMA if operating in the FH mode. Table 1 provides a summary of the spectral efficiencies achieved by each system is provided as a reference from which to judge the current commercial and emerging technologies.

System Description	W	C	η
SINCGARS (CSMA/FDMA/FH/TDD)	25 kHz	9.6 kbps	0.384
Enhanced Position Location Reporting System (EPLRS) (TDMA/TDD)	6 MHz	288 kbps	0.048
Near-Term Digital Radio (NTDR) WideBand (TDMA/TDD)	4 MHz	500 kbps	0.125
Near-Term Digital Radio (NTDR) NarrowBand (TDMA/TDD)	500 kHz	500 kbps	1.00

Table 1 Spectral Efficiencies of Common Brigade C2 systems

7. Future RF technology

In order to gain a perspective on the spectral efficiencies of various modulation schemes, it was necessary to look at several schemes that are currently in commercial use. When looking at wireless standards, it is apparent that the various cellular and wireless LAN technologies lead the industry. Table 2 below lists various standards and the spectral efficiencies.

Standard	Description	W	C	η
IS-136	D-AMPS First US Digital Cellular Phone Standard (TDMA/FDD)	30 kHz	48 kbps	1.6
GSM	Global Digital Cellular Phone Standard (TDMA/FDD)	200 kHz	270 kbps	1.35
802.11b	IEEE Wireless LAN Standard (PLCP/DSSS/FH)	10 MHz	11 Mbps	1.1
IS-95	2nd Generation US Cellular Phone Standard (CDMA/FDD)	1.25 MHz	1.23 Mbps	0.98
802.11a	IEEE Wireless LAN Standard (PLCP/OFDM)	30 MHz	54 Mbps	1.8
IMT-2000	W-CDMA 3rd Gen European Wireless Standard (CDMA/FDD)	800 kHz	2 Mbps	2.5
IS-2000	CDMA2000 3rd Gen US Wireless Standard (CDMA/OFDM)	1.25 MHz	4.9 Mbps	3.92
None	BLAST Next Gen Wireless (CDMA/OFDM+STC) Per Dimension	51 kHz	1.35 Mbps	4.4
Theory	Shannon's Theoretical Efficiency Limitation (S/N=30dB)			9.96

Table 2. Various Wireless Standards and their high-end spectral efficiencies

This list of spectral efficiencies shows the increasing trend in spectral efficiency as the demand for higher data rate mobile communications has increased over recent years. 3rd generation systems are currently being engineered with several solutions scheduled to be rolled out in 2002.

7.1 Third Generation Wireless Techniques

There are several variants of third generation wireless schemes; all of them are based on the ITU IMT-2000 series of recommendations. The goal of IMT-2000 is to provide a framework that will allow all future wireless systems to interoperate globally. Some of these objectives of IMT-2000 [11] are to:

- Establish a single global system for wireless communications
- Ensure multi-environment operation (Vehicular, Pedestrian and Outdoor-to-Indoor, Indoor Office and Satellite)
- Support voice, data and multimedia video services at a minimum user rate of 2 Mbps indoor and 144kbps outdoor
- Ensure that a single handset can operate in all allocated spectrums, regardless of country

There are currently two very similar standards that have been developed to meet the IMT-2000 goals [12]: W-CDMA, the standard being developed by Europe and Japan; and CDMA2000, the standard adopted by the EIA/TIA for the United States. These two standards differ mainly in that W-CDMA will be backwards compatible with existing GSM handsets and CDMA2000 will be backwards compatible with existing IS-95 networks as shown in Figure 4. Since both standards are similar and provide interoperability and meet IMT-2000 prescribed recommendations, we will discuss the CDMA2000 standard and its possible application in military networks.

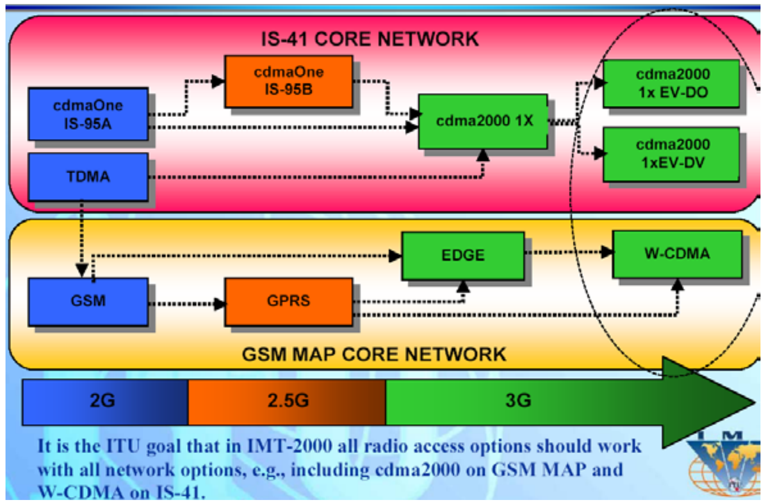

Figure 4. Evolution Paths of GSM and IS-95 [12]

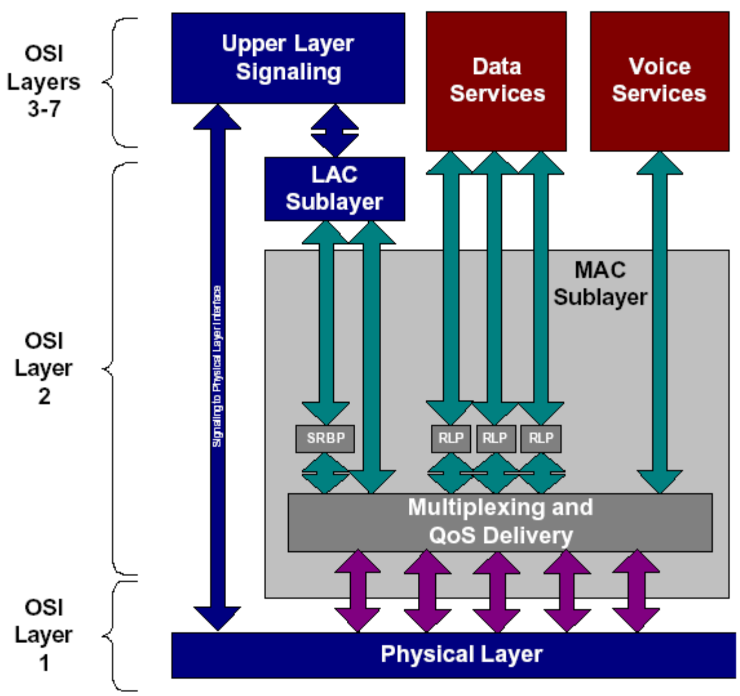

Figure 5. cdma2000 Layered Structure [13]

The layered model shown in Figure 5 shows that CDMA2000 family of specifications includes the core air interface, minimum performance, and service standards with QoS provided for both voice and data services within the standard.

The cdma2000 physical layer standard is described in EIA/TIA-IS-2000.2-A-1. It is capable of operating in 10 different worldwide frequency bands [14], making it easily adaptable to the military assigned spectrum with minor transmitter and receiver modifications. A physical layer model is shown in Figure 6. Different schemes are used in the Downlink (base→ mobile) and uplink (mobile → base). The multi-carrier (MC) technique used in the downlink direction is an Orthogonal Frequency Division Multiplexing (OFDM) technique similar to the 802.11a and DSL.DMT standards. OFDM is similar to FDD except that, by ensuring each frequency band is orthogonal, no guard band is needed between frequency channels, dramatically enhancing efficiency and allowing the potential for future frequency hopping to increase security (although this is not specifically mentioned in the CDMA2000 standard, it is technically feasible). In the downlink direction, Direct Sequencing (DS) is used [15]. DS spreads the Power Spectral Density (PSD) of the signal across a wide band. It is slightly less efficient and has a slightly lower range than MC, but its use of lower power and reduced latency (as compared to FH) make it less susceptible to detection and jamming.

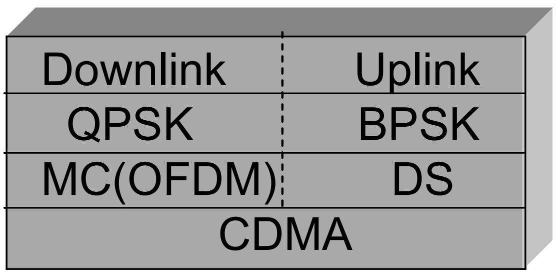

Figure 6. CDMA2000 Physical Layer

The underlying access technique is CDMA. CDMA uses the spectrum more efficiently than TDMA or FDMA. It has several advantages including: increased capacity, enhanced privacy and security, improved coverage characteristics, co-existence with other technologies with little to no interference, and reduced interference with other electronic devices. The multi-carrier and CDMA combination are the most efficient techniques available in the commercial market today as was evident in the list shown in Table 1. There are, however, new technologies in development that will far surpass these efficiencies.

7.2 Next Generation Wireless Techniques

Several advances in spectral efficiency have been researched; the most promising next generation technique that may increase spectral efficiency by more than a factor of ten is called BLAST (Bell-Labs Layered Space Time). Considerable academic research has been dedicated to this area as well as and experimentation by the Defense Advanced Research Projects Agency (DARPA).

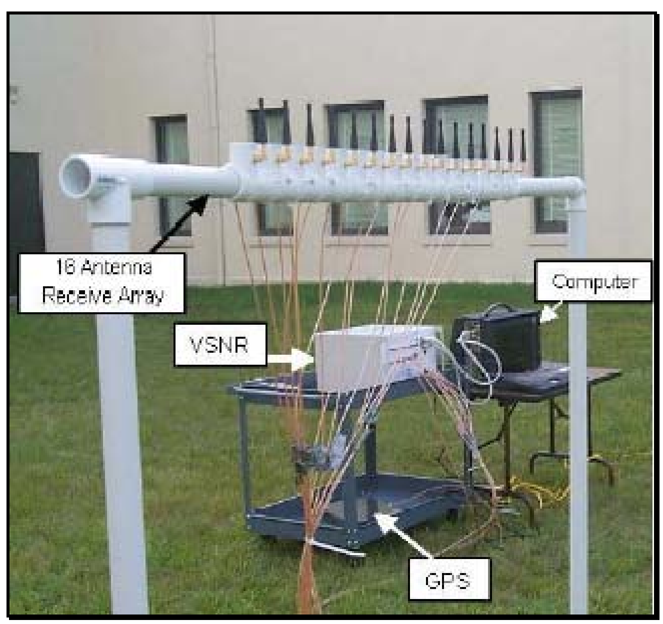

Figure 7. BLAST Transmitter & Antenna Array [16]

BLAST uses the concept of a multi-element antenna array (MEA) that transmits different signals in the same bandwidth over several antenna elements simultaneously (sub-channels); taking advantage of the fact the transmitted signals from each antenna will not travel the exact same distance and path to the receiver's antenna array. A picture of the system tested by DARPA is shown in Figure 7. The channel capacity of an MEA is the sum of capacities of these sub-channels [17]. Multiple antenna systems provide very high capacity compared to single antenna systems in a Rayleigh fading environment [18]. Space-time codes are used on each subchannel; these channel codes are designed to utilize this high capacity without requiring instantaneous channel state information at the transmitter**.** [19]

Vertical BLAST, or V-BLAST, which has been implemented in realtime in laboratories. Using this laboratory prototype, we have demonstrated spectral efficiencies as high as 40bit/s/Hz. A system diagram of V-BLAST is shown in Figure 8.

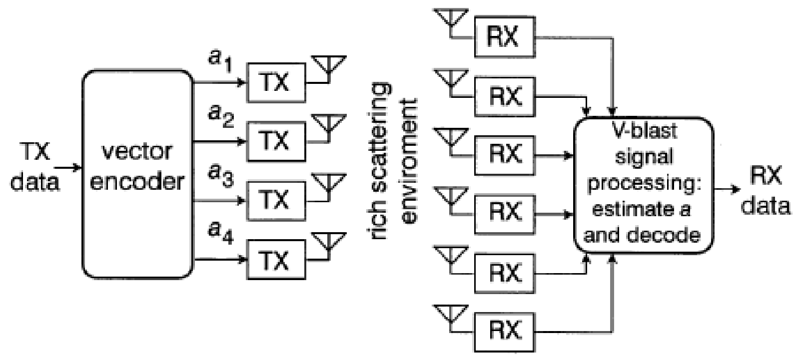

Figure 8. V-BLAST High-Level System Diagram [20]

The best advantage of V-BLAST, besides its increased spectral efficiency, is that the MEA technology is best suited for, and has been tested with a CDMA-OFDM scheme similar to that used by CDMA2000 [21]. The largest upgrade factor for BLAST would be the addition of the antenna array on top of existing hardware. The disadvantage of using MEAs are the size associated with the antenna system. This may cause a problem for the commercial handheld market, but is well suited to vehicular platforms used in military applications.

8. The proposed future RF battlefield

Joint Vision 2010 declared and Joint Vision 2020 reiterated that the ultimate objective of US forces is to be dominant across the full spectrum of military operations, by being persuasive in peace, decisive in war, and preeminent in any form of conflict. One of the key enablers of achieving this vision is the concept of information superiority.[22] Joint Pub 1-02 defines this concept as the capability to collect, process, and disseminate an uninterrupted flow of information while exploiting or denying an adversary's ability to do the same. The RF systems the US use now and will use in the foreseeable future will continue to enable the US to achieve this objective. Figure 9 represent the relationship of Information Superiority to the other Joint Vision tenets.

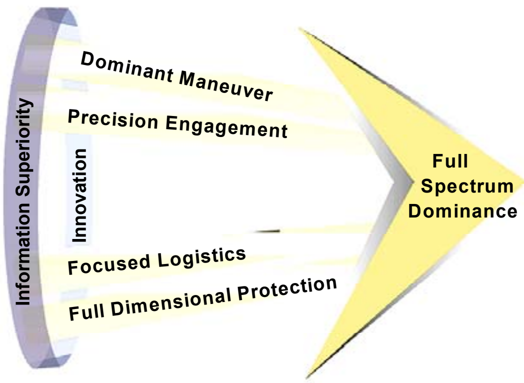

Figure 9

The ever increasing employment of emitters within the battlespace will mandate that efficiency improvements continue to be made to RF systems. The combination of intelligent, GPS equipped, Software Defined Radios and validated discrete event system simulation models offer great promise for a paradigm shift from static frequency assignment to dynamic frequency selection. If the radios in a network are able to become situationally aware of their RF environment then it has the potential to increase achievable utilization rates many fold. Aspects of these smart systems are evident programs like SUOSAS and the NeXt Generation Communication work being performed under the direction of DARPA.[23]

Broadcast power management will always be a critical factor in an emitter rich environment. The ability of a system to adjust its transmits power to minimal acceptable levels allows for more systems to coexist within the same RF space with minimal interference. As stated earlier, broadcast power management also improves transmission security because it minimizes the risk of enemy detection of RF signature of the transmitter.

Improvements in RF antenna technology will also be an enabler in achieving Joint Vision 2020 objectives. Antennas that perform efficiently across multiple bands will allow intelligent radios to transmits across a wide operating range of frequencies while reducing the likely hood of spurious emissions.

The writers of Joint Vision 2020 stated that innovation will also be a key enabler in reaching the objective and improving spectral efficiency offers many opportunities for individuals to innovate.

9. Keys to Army Frequency Management Success

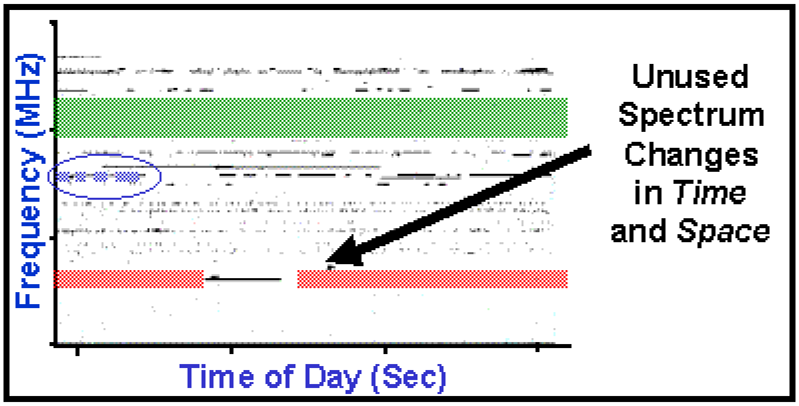

Figure 10. Unused Spectrum over Time[23]

Figure 10 is a DARPA representation of the statistical nature of RF spectrum access. The figure clearly shows that there are many instances where available spectrum is under utilized. If the Army is to be successful it must increase the utilization rate of every available segment of RF spectrum. The most important initial step is to identify what are the Army actual spectral requirements and the rate at which systems attempt to gain spectrum access.

Many organizations like the Initial Brigade Combat Team at FT Lewis and III Corps at FT Hood are actively attempting to quantify and ensure they spectral requirements are refined. Once this data collected it can be used to form the basis of a simulation model. The ability to model live network traffic is the best way to test various scenarios without risking lives or property.

The Spectrum Analysis and Modeling System (SAMS) being developed for the Army Spectrum Manager, at Fort Gordon GA, displays the potential to accurately simulate RF spectral utilization of an IBCT. The intent is to use the Next Generation Performance Model, which is the high-resolution tactical internet model at brigade and below, to produce a pattern of RF emissions. The result of this type of simulation will assist in the analysis and planning of current and future technological insertions.

10. Conclusion

The RF spectrum is finite and its availability is as vital to the Army as bullets and fuel. The commercial communications industry will continue its assault on DOD spectral resources and the best recourse for DOD is to prove that we are being efficient and responsible stewards of the RF Spectrum that has been allocated for our use. This approach has several positive benefits;

- Ensures that the Army maintains a technological edge on any potential foe.
- Enables the Army to meet its transformation information superiority goals earlier.

11. References

[1] Newhouse, Elizabeth Ed., Inventors and Discoverers, National Geographic Society, Washington DC, 1988. pg 185-187

[2] http://chppm-www.apgea.army.mil/rfup/website/fig1.htm

[3] Coker, Kathy and Rios, Carol, A Concise History of the U.S. Army Signal Corps, Office of the Command Historian, US Army Signal Center and Fort Gordon, 1988. pg 15

[4] Russell, Steve F. *Wireless Channel Security Tutorial* 1996, Electrical and Computer Engineering Iowa State University, Ames, Iowa, 2000.

[5] C. E. Shannon, "A mathematical theory of communication," *The Bell System Technical Journal,* Vol. 27, July, October, 1948. pp. 379–423, 623–656

[6] NTIA Manual of Regulations & Procedures for Federal Radio Frequency Management, 2000 Edition with Jan/May/Sep Revisions: http://www.ntia.doc.gov/osmhome/redbook/redbook.html

[7] Department of the Army, Army Regulation 5-12, *Army Management of the Electromagnetic Spectrum* (Department of the Army, 1997), 14

[8] Evci, Cengiz "Optimizing and Licensing the Radio Frequency Spectrum for Terrestrial 3G users" *Alcatel Telecommunications Review* First Quarter 2001, 20

[9] Anderson, David S., Drocella, Edward F., Jones, Steven K., Settle, Mark, "Assessment of Compatability Between Ultrawideband (UWB) Systems and Global Positioning System (GPS) Receivers" *NTIA Special Publication 01-45, February 2001*

[10] Department of the Army, Army Regulation 5-12, *Army Management of the Electromagnetic Spectrum* (Department of the Army, 1997), 8-10

[11] M.687-2, *International Mobile Telecommunications-2000 (IMT-2000)*, International Telecommunications Union, Feb 1997.

[12] http://www.itu.int/osg/imt-project/

[13] TIA/ EIA/ IS- 2000.1- A, "Introduction for cdma2000 Standards for Spread Spectrum Systems" *Telecommunications Industry Association 2000 Standards & Technology Department,* March 2000.

[14] TIA/EIA/IS-2000.2-A-1, "Physical Layer Standard for cdma2000 Spread Spectrum Systems" *Telecommunications Industry Association 2000 Standards & Technology Department,* 2000.

[15] TIA/EIA/TR45.5.4, "cdma2000 System Description" *Telecommunications Industry Association 2000 Standards & Technology Department,* 2000.

[16] http://www.darpa.mil/

[17] Da-Shan Shiu, Gerard J. Foschini, Michael J. Gans, and Joseph M. Kahn, " Fading Correlation and Its Effect on the Capacity of Multielement Antenna Systems", IEEE Transactions On Communications, Vol. 48, No. 3, March 2000

[18] Gerard J. Foschini, Glen D. Golden, Reinaldo A. Valenzuela, and Peter W. Wolniansky, "Simplified Processing for High Spectral Efficiency Wireless Communication Employing Multi-Element Arrays", IEEE Journal On Selected Areas In Communications, Vol. 17, No. 11, November 1999.

[19] Da-shan Shiu and Joseph M. Kahn, *Design of High-Throughput Codes for Multiple-Antenna Wireless Systems*, Department of Electrical Engineering and Computer Sciences. University of California - Berkeley, 1999

[20] Golden, C.J., Foschini, R.A., Valenzuela and P.W. Wolniansky. "Detection Algorithm And Initial Laboratory Results Using V-BLAST Space-Time Communication Architecture", Electronics Letters, January 1999 Vol. 35 No. 1

[21] D. Marabissi, E. Del Re, R. Fantacci, S. Morosi., *Selective Parallel Interference Cancellation for a WCDMA Communications with Antenna Array*, Department of Electronics and Telecommunications - University of Firenze, Italy, 1999.

[22] Joint Vision 2020 [database online] available online http://www.dtic.mil/jv2020 accessed March 5, 2002

[23] "Shuffling the Spectrum Deck", Signal March 2002, pp 35-38

[24] Agilent Technologies, Wireless Dictionary available online http://www.agilent.com

Useful Links

http://www.umts-forum.org/
http://www.ntia.doc.gov/
http://www.fcc.gov/3G/
http://www.imt-2000.org/portal/index.asp
http://www.itu.int/osg/imt-project/
http://www.3gamericas.org/English/index.cfm

List of Acronyms [24]

AMPS	Advanced Mobile Phone System	The original standard specification for analog systems. Operates in the frequency range of 800 MHz, with a bandwidth of 30kHz. Used primarily in North America, Latin America, Australia and parts of Russia and Asia.
antenna		The part of a radio transmission system designed to radiate or receive electromagnetic waves.
ASIC	Application-Specific Integrated Circuit	An integrated circuit designed to perform a specific set of functions, usually within a specific device.
AWGN	Additive White Gaussian Noise	Statistically random radio noise characterized by a wide frequency range with regards to a signal in a communications channel.
band		In wireless communication, band refers to a frequency or contiguous range of frequencies. Currently, wireless communication service providers use the 800 MHz, 900 MHz and1900 MHz bands for transmission in the United States.
bandwidth		The information-carrying capacity of a communications channel. Usually expressed in Hertz (cycles per second) for analog circuits and in bits per second (bps) for digital circuits.
baseband signal		A signal with frequency content centered around DC. Typically the modulating signal for an RF carrier.
bps	Bits per Second	The units usually used to express data transmission speed; the number of pieces of information transmitted per second.
BPSK	Binary Phase Shift Keying	A type of phase modulation using 2 distinct carrier phases to signal ones and zeros.
BS	Base Station	The equipment on the network side of a wireless communications link. The base station contains the tower, antennas and radio equipment needed to allow wireless communications devices to connect with the network.
CDMA	Code Division Multiple Access	One of several digital wireless transmission methods in which signals are encoded using a specific pseudo-random sequence, or code, to define a communication channel. A receiver, knowing the code, can use it to decode the received signal in the presence of other signals in the channel. This is one of several "spread spectrum" techniques, which allows multiple users to share the same radio frequency spectrum by assigning each active user an unique code. CDMA offers improved spectral efficiency over analog transmission in that it allows for greater

		frequency reuse. Other characteristics of CDMA systems reduce dropped calls, increase battery life and offer more secure transmission. See also IS-95.
cdma2000	The name identifying the TIA standard (IS-2000) for third generation technology.	A radio transmission technology for the evolution of IS-95 to 3rd-generation adding up multiple carriers. See also W-CDMA for single carrier/direct spread technology.
channel		A general term used to describe a communications path between two systems. They may be either physical or logical depending on the application. An RF channel is a physical channel, whereas control and traffic channels within the RF channel would be considered logical channels.
D-AMPS	Digital-Advanced Mobile Phone System	Earlier designation of American standard for digital mobile telephony used primarily in North America, Latin America, Australia and parts of Russia and Asia. Also known as (North American) TDMA. See also TDMA and IS-136.
delay spread		A type of distortion due to multipath resulting in the spreading out or "smearing" of the received signal. It occurs when identical signals arrive via different paths and have different time delays.
digital		Describes when information - speech, for example - is encoded before transmission using a binary code - discrete, non-continuous values. Digital networks are rapidly replacing analog ones as they offer improved sound quality, secure transmission and can handle data as well as voice. Digital networks include mobile systems GSM 900, GSM 1800, GSM 1900, D-AMPS and the cordless DECT system.
diversity		A technique to reduce the effects of fading by using multiple spatially separated antennas to take independent samples of the same signal at the same time. The theory is that the fading in these signals is uncorrelated and that the probability of all samples being below a threshold at a given instant is low.
downlink		The transmission path from the base station down to the mobile station.
DS	Direct Sequence	A process of spectrum spreading where the digital information stream is multiplied, using an exclusive OR technique, by a high speed pseudorandom code (spreading sequence) to generate a spread spectrum signal.
EDGE	Enhanced Data for Global Evolution	A technology that gives GSMA and TDMA similar capacity to handle services for the third generation of mobile telephony. EDGE was developed to enable the transmission of large amounts of data at a high speed, 384 kilobits per second. (It increases available time slots and

		data rates over existing wireless networks.)
EIA	Electronic Industry Association	A trade association and standards setting organization in the USA.
fading		The variation in signal strength from it normal value. Fading is normally negative and can be either fast or slow. It is normally characterized by the distribution of fades, Gaussian, Rician, or Rayleigh.
FCC	Federal Communications Commission	Regulatory body governing communications technologies in the US. established by the Communications Act of 1934, as amended, and regulates interstate communications (wire, radio, telephone, telegraph and telecommunications) originating in the United States.
FDD	Frequency Division Duplex	Radio technology using a paired spectrum. Used in cellular communication systems such as GSM.
FDMA	Frequency Division Multiple Access	Method of allowing multiple users to share the radio frequency spectrum by assigning each active user an individual frequency channel. In this practice, users are dynamically allocated a group of frequencies so that the apparent availability is greater than the number of channels.
FH	Frequency Hopping	A periodic changing of frequency or frequency set associated with transmission. A sequence of modulated pulses having a pseudorandom selection of carrier frequencies.
FHMA	Frequency Hopped Multiple Access	A set of frequency hopping communicators operating as a system to provide communications services. All communicators traditionally use the same set of carrier frequencies and coordinate their hopping sequences to minimize interference in the network. [1]
FHSS	Frequency Hopped Spread Spectrum	A spectrum spreading technique using an RF carrier hopped across a large number of RF channels using a random or pseudorandom code to determine the sequence of channels used.
FSK	Frequency Shift Keying	A form of modulation using multiple carrier frequencies to carry the digital information. The most common is the two frequency FSK system using the two frequencies to carry the binary ones and zeros.
GMSK	Gaussian Minimum Shift Keying	A modulation technique involving Gaussian filtering of the input data prior to its application to the phase modulator. This results in a narrow occupied spectrum and better adjacent channel interference performance.
GPRS	General Packet Radio Service	A packet-linked technology that enables high-speed (115

		kilobit per second) wireless Internet and other data communications over a GSM network. It is considered an efficient use of limited bandwidth and is particularly suited for sending and receiving small bursts of data.
GSM	Global System for Mobile Communication	Originally developed as a pan-European standard for digital mobile telephony, GSM has become the world's most widely used mobile system. It is used on the 900 MHz and 1800 MHz frequencies in Europe, Asia and Australia, and the MHz 1900 frequency in North America and Latin America.
GSM 1800	A digital network working on a frequency of 1800 MHz.	It is used in Europe, Asia-Pacific and Australia. Also known as DCS 1800 or PCN.
GSM 1900	A digital network working on a frequency of 1900 MHz.	It is used in the US and Canada and is scheduled for parts of Latin America and Africa. Also known as PCS 1900.
GSM 900		GSM 900, or just GSM, is the world's most widely used digital network and now operating in over 100 countries around the world, particularly in Europe and Asia Pacific.
guard band		A set of frequencies or band-width used to prevent adjacent systems from interfering with each other. Guard bands are typically used between different types of systems at the edges of the frequency allocations.
HPSK	Hybrid Phase Shift Keying	The spreading technique used in the reverse link of 3G systems to reduce the peak-to-average ratio of the signal by reducing zero crossings and 0 degree phase transitions. Also known as Orthogonal Complex Quadrature Phase Shift Keying (OCQPSK).
Hz	Hertz	A radio frequency measurement (one hertz = one cycle per second).
IMT-2000	International Mobile Telecommunication 2000	A term used by the International Telecommunication Union, a United Nations agency, to describe the third generation mobile telephony due to be ready in 2000. Can also be applied to mobile telephone standards that meet a number of requirements in terms of transmission speed and other factors.
IS-136	EIA Interim Standard 136 - NADC with Digital Control Channels	The North American digital mobile telephony standard based on TDMA technology. It is the version of the TDMA specification resulting in a fully digital 2nd generation system and is backward compatible with analog AMPS. See also TDMA and D-AMPS.
IS-2000	EIA Interim Standard 2000 (see cdma2000)	A standard for current CDMA systems providing a migration path to 3G services.
IS-41	Inter-network connection protocol for	Inter-network connection protocol for connecting systems

	connecting systems based on both analog and digital US standards.	based on both analog and digital US standards.
IS-54	EIA Interim Standard for U.S. Digital Cellular	Original TDMA digital standard. Implemented in 1992. This standard was the first to permit the use digital channels in AMPS systems. It used digital traffic channels but retained the use of analog control channels. This standard was replaced by the IS-136 digital standard in 1996.
IS-95	EIA Interim Standard 95	The original digital mobile telephony standard based on CDMA technology. See also CDMA.
ITU	International Telecommunications Union	A United Nations agency that deals with telecommunications issues.
kHz	kiloHertz	A radio frequency measurement (one kilohertz = one thousand cycles per second).
LOS	line of sight	A description of an unobstructed radio path or link between the transmitting and receiving antennas of a communications system.
MC-CDMA	Multi-Carrier Code Division Multiple Access	Typically, this means the combination of three IS-95 carriers to form one wideband carrier. It is an evolution of IS-95 for third generation systems. Also called cdma2000. The current nomenclature is temporary, with a formal name for this technology to be determined under 3GPP2.
MHz	Megahertz	A unit of frequency equal to one million hertz or cycles per second. Wireless communications occur in the 800 MHz, 900 MHz and 1900 MHz bands.
multipath		A propagation phenomenon characterized by the arrival of multiple versions of the same signal from different locations shifted in time due to having taken different transmission paths of varying lengths.
multiple access		The process of allowing multiple radio links or users to address the same radio channel on a coordinated basis. Typical multiple access technologies include FDMA, TDMA, CDMA, and FHMA.
N-AMPS	Narrowband Advanced Mobile Phone System	Combines the AMPS transmission standard with digital signaling information to effectively triple the capacity of AMPS while adding basic messaging functionality.
Nyquist rate		The minimum sampling rate proposed by Nyquist for converting a band limited waveform to digital pulses. The rate must be at least twice the highest frequency of interest in the waveform being sampled.
OFDM	Orthogonal Frequency Division	A modulation technique that transmits blocks of symbols

	Multiplex	in parallel by employing a large number of orthogonal subcarriers. The data is divided into blocks and sent in parallel on separate sub-carriers. By doing this, the symbol period can be increased and the effects of delay spread are reduced.
OQPSK	Offset Quadrature Phase Shift Keying	A type of QPSK modulation that offsets the bit streams on the I and Q channels by a half bit. This reduces amplitude fluctuations and helps improve spectral efficiency.
packet radio		A radio system that operates by sending data in packets.
path loss		The amount of loss introduced by the propagation environment between a transmitter and receiver.
PSD	power spectral density	Power normalized to 1 Hz. Knowing the power spectral density and system bandwidth, the total power can be calculated.
propagation		The process an electromagnetic wave undergoes as it is radiated from the antenna and spreads out across the physical terrain. See also propagation channel.
PSK	Phase Shift Keying	A broad classification of modulation techniques where the information to be transmitted is contained in the phase of the carrier wave.
QAM	Quadrature Amplitude Modulation	A type of modulation where the signalling information is carried in the phase and amplitude of the modulated carrier wave.
QPSK	Quadrature Phase Shift Keying	A type of phase modulation using 2 pairs of distinct carrier phases, in quadrature, to signal ones and zeros.
RF	radio frequency	Electromagnetic waves in the frequency range of 30 kHz to 300 GHz.
SDMA	Space Division Multiple Access	Also known as multiple beam frequency reuse, this technique employs spot beam antennas to reuse frequencies by pointing the antenna beams using the same frequency in different directions.
S/N	signal-to-noise ratio	The ratio of power in a signal to the noise power in the channel. This term is usually applied to lower frequency signals, such as voice waveforms.
spread spectrum		A term used to describe a system that uses spectrum spreading techniques in its operation.
TDD	Time Division Duplex	A duplexing technique dividing a radio channel in time to allow downlink operation during part of the frame period and uplink operation in the remainder of the frame period.

TDMA	Time Division Multiple Access	A technology for digital transmission of radio signals between, for example, a mobile telephone and a radio base station. In TDMA, the frequency band is split into a number of channels which in turn are stacked into short time units so that several calls can share a single channel without interfering with one another. Networks using TDMA assign 6 timeslots for each frequency channel. TDMA is also the name of a digital technology based on the IS-136 standard. TDMA is the current designation for what was formerly known as D-AMPS. See also IS-136 and D-AMPS.
transmitter		Equipment which feeds the radio signal to an antenna, for transmission. It consists of active components such as the mixer, driver and PA and passive components such as the TX filter. Taken together, these components impress a signal onto an RF carrier of the correct frequency by instantaneously adjusting its phase, frequency, or amplitude and provide enough gain to the signal to project it through the ether to its intended target.
UHF	Ultra High Frequency	The RF spectrum between 300 MHz and 3 GHz.
UMTS	Universal Mobile Telecommunications System	Third generation telecommunications system based on WCDMA DS.
uplink		The transmission path from the mobile station up to the base station.
VHF	Very High Frequency	The RF spectrum between 30 MHz and 300 MHz.
Walsh Code		A group of spreading codes having good autocorrelation properties and poor crosscorrelation properties. Walsh codes are the backbone of CDMA systems and are used to develop the individual channels in CDMA. For IS-95, here are 64 codes available. Code 0 is used as the pilot and code 32 is used for synchronization. Codes 1 though 7 are used for control channels, and the remaining codes are available for traffic channels. Codes 2 through 7 are also available for traffic channels if they are not needed. For cdma2000, there exists a multitude of Walsh codes that vary in length to accommodate the different data rates and Spreading Factors of the different Radio Configurations.
W-CDMA	Wideband-Code Division Multiple Access	A 3G radio interface using DSSS, and both Frequency Division (FDD) and Time Division Duplexing (TDD) depending on the frequency assignment. The earlier Japanese W-CDMA trial system and the European UMTS have both served as a foundation for the workings of the current harmonized W-CDMA system, under the supervision of the 3GPP.